The Origins of the XMM-Newton Reflection Grating Spectrometer

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Overview of the RGS Experiment

* RGS incorporates an array of reflection gratings (RGA), which "picks off" ~ 40% of the light exiting the telescope and disperses it to a dedicated focal plane camera (RFC), consisting of 9 rectangular, back-illuminated CCDs arranged in a strip.

* There are two identical such units, RGS1 and RGS2, mounted behind the MM2 and MM3 telescopes, respectively. The remaining light from each of these two telescopes passes, undeflected through the RGAs to the EPIC-MOS cameras.

* RGS provides high sensitivity, high resolution, X-ray spectroscopy in the wavelength range *5 - 35 Angstroms*, or *E = 0.35 - 2.5 keV*. This is a line-rich region of the spectrum, which contains the prominent *K*-shell transitions of low-*Z* abundant elements (C, N, O, Ne, Si) and the diagnostically-important *L*-shell transitions of Fe.

* The RGS operates simultaneously with EPIC. RGS spectra of sources in the field of view are obtained for every XMM observation.

Unique Capabilities of the RGS

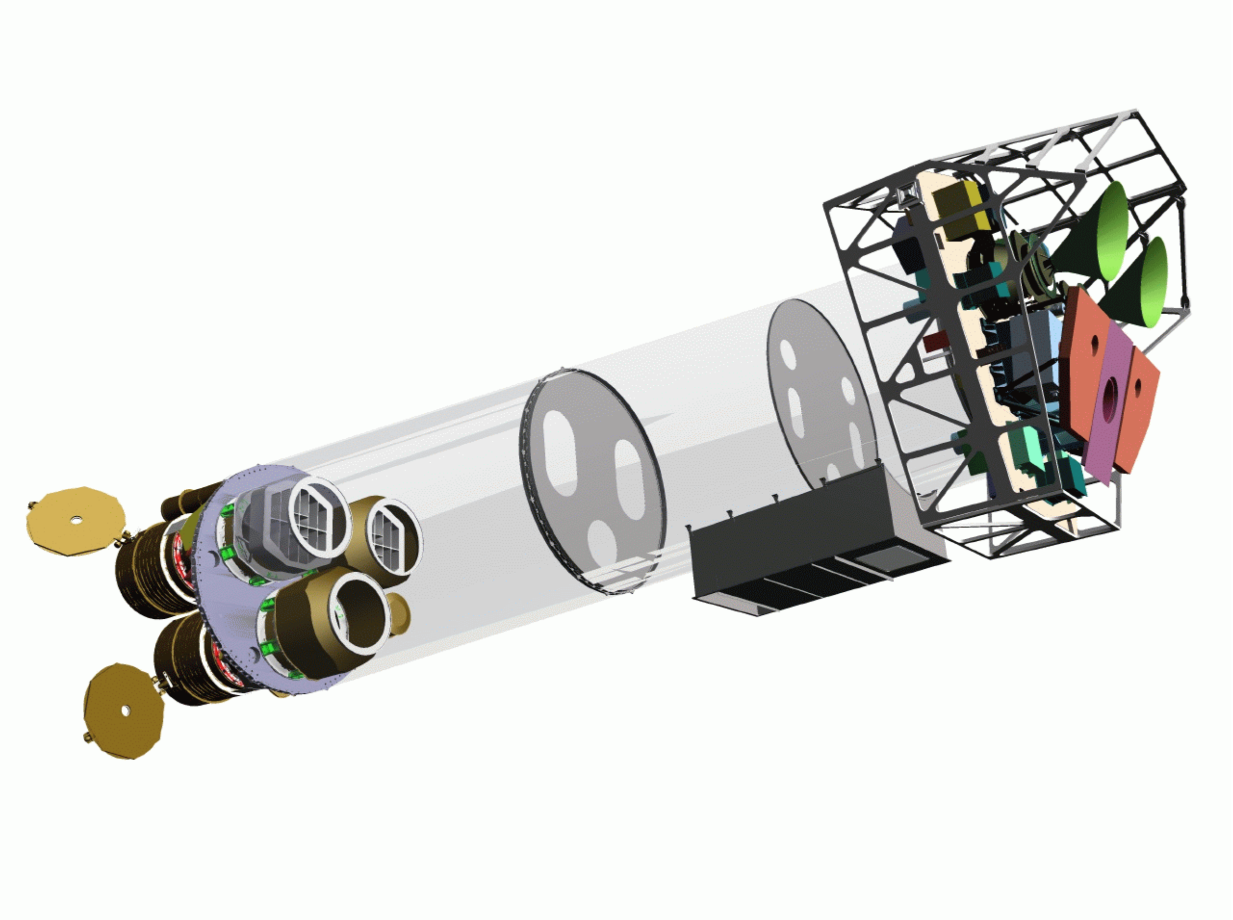
* RGS provides an unparalleled combination of effective area and resolution at energies between *0.35* and ~ *1.5 keV*.

* This band includes the important He-like lines of nitrogen, oxygen, and neon, as well as the $n = 3 - 2$ L-shell transitions of iron. The resolution is sufficient to unambiguously resolve these lines, which is essential for model-independent interpretations of the spectrum.

* Although it is a slitless spectrometer, RGS also obtains reasonably high resolution spectra of *moderately extended* sources ($\Delta\theta <$ *few arcminutes*). This is because the dispersion is very high, much higher, for example, than the transmission grating spectrometers on *Chandra*.

* RGS spectra are obtained in parallel with imaging studies performed with EPIC, and are available for every observation conducted with XMM. This makes the experiment ripe for serendipitous discovery of unusual spectroscopic features in either the target source, or other sources in the field.

Layout of the RGS on the *XMM-Newton* Spacecraft



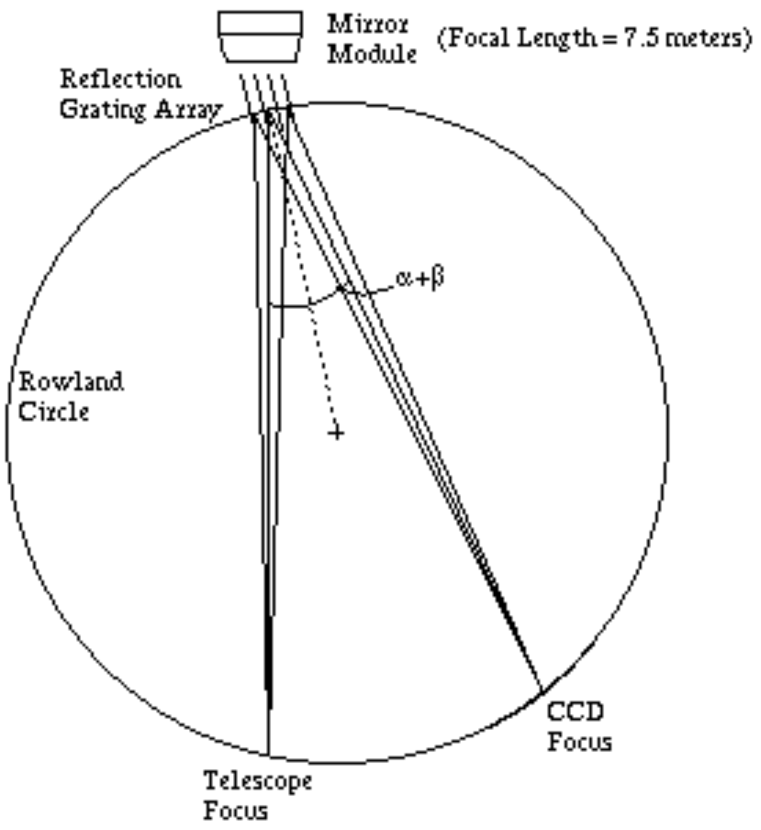
The Optical Design of RGS

* The RGS uses an "inverted Rowland circle" design. The gratings are mounted on a circle, which also includes the telescope focus and the RFC CCD strip.

* The gratings are all identical, and they are mounted at the same graze angle with respect to the incident ray passing through grating center.

* This configuration produces nearly stigmatic and aberration-free focussing at all wavelengths in the spectrum.

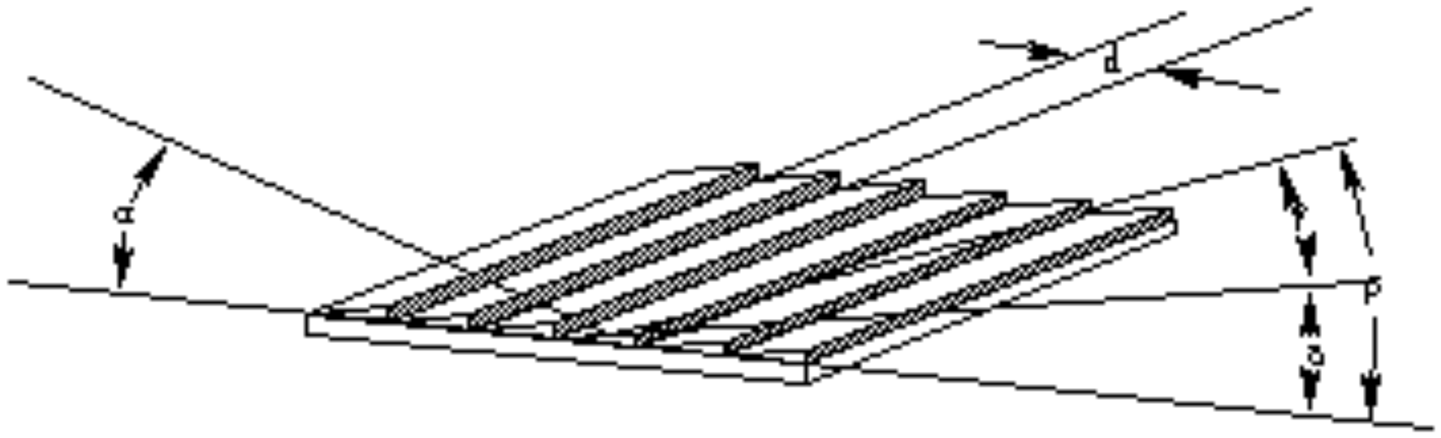
* The line spacing on the individual gratings is varied to correct for aberrations due to the converging bream.



The Optical Design of RGS

* The gratings are mounted in the “in-plane” configuration, where the light comes in at normal incidence to the grooves.

* The grooves are “blazed” to achieve maximum diffraction efficiency in first order at a wavelength of 15 Angstroms. The blaze angle is 0.7 degrees, and the groove density is 646 lines/mm.



Design Optimization

The grating equation gives:

$$m\lambda = d(\cos\alpha - \cos\beta)$$

At the blaze:

$$m\lambda = 2d\ \sin\gamma\ \sin\delta$$

The efficiency of the system at blaze is roughly:

$$Eff_B \approx \eta^2 R(\gamma)$$

where:

$$\eta = \sin\alpha\ /\ \sin\beta_B$$

The resolving power at blaze is roughly:

$$\left(\frac{\lambda}{\Delta\lambda}\right)_B \approx \frac{\gamma}{\Delta\theta}\left(\frac{1}{\eta} - 1\right)$$

Not surprisingly, high efficiency (low γ, high η) implies low resolving power and visa versa. For the RGS, we looked for moderate resolution with good efficiency, which gave $\gamma = 2.27°$, and $\eta = 0.53$.

So how did all this come about?

- As a Center Postdoctoral Fellow at the CfA, I became interested in higher resolution spectroscopy, and I started working with the transmission grating data on *Einstein* and EXOSAT.

- The results were very interesting, but it was clear that we needed both higher resolution and much higher effective area to expand the science. I started working with Paul Gorenstein on design studies for *LAMAR*, a prototype US concept for a large area X-ray spectroscopy mission. We were looking at objective reflection grating arrays, which fit in naturally with the Kirkpatrick-Baez geometry invoked in the *LAMAR* concept. Initially, we had these in front of the mirror, which was non-optimal for a number of reasons.

- I continued this work after moving to Columbia as an assistant professor, during which time I moved to the UK for 7 months to work on EXOSAT. It was there, that I spent time with France Cordova and Keith Mason, but also got much more ingrained in the European community.

First Ideas for the RGS

- In 1984, I moved to Berkeley. There, I encountered Mike Hettrick, who had designed the reflection grating spectrometer for *EUVE*. *EUVE* incorporated gratings behind the telescope, but each grating had its own telescope. To account for the converging beam, Hettrick invented the variable line-space grating.

- At this point, *LAMAR* was dead, and given my European experience, I started thinking about *XMM*. Given the much smaller graze angles required for X-rays, Hettrick and I worked out designs for arrays of reflection gratings. I was the one who invented the Inverted Rowland Circle geometry, but this didn't come to me directly – I had to draw out lines of converging rays to figure it out.

- In late 1984, I went to the Lyngby meeting to present this idea as a poster.

- I wasn't expecting a big reaction, but that meeting was dominated by debates over whether the mission needed both high resolution smaller telescopes and lower resolution larger telescopes. The discussion made clear that the need for the smaller telescopes was driven by the lower dispersion provided by transmission gratings, which were planned as the dispersing elements. At one point, Piet de Korte, from Leiden, stood up and said that there was a poster in the back which indicated that we could obtain the same or better spectral resolution with the lower angular resolution telescopes, if we used reflection gratings instead of transmission gratings.

- When I got back to Berkeley, I wrote letters to de Korte, and to Tony Peacock (the XMM Project Scientist) suggesting that we collaborate on developing a reflection grating concept for XMM.

- That began the collaboration with SRON in Utrecht, where I met Bert Brinkman, Rolf Mewe, Ton den Boggende, and a young Frits Paerels!

How did this get funded?

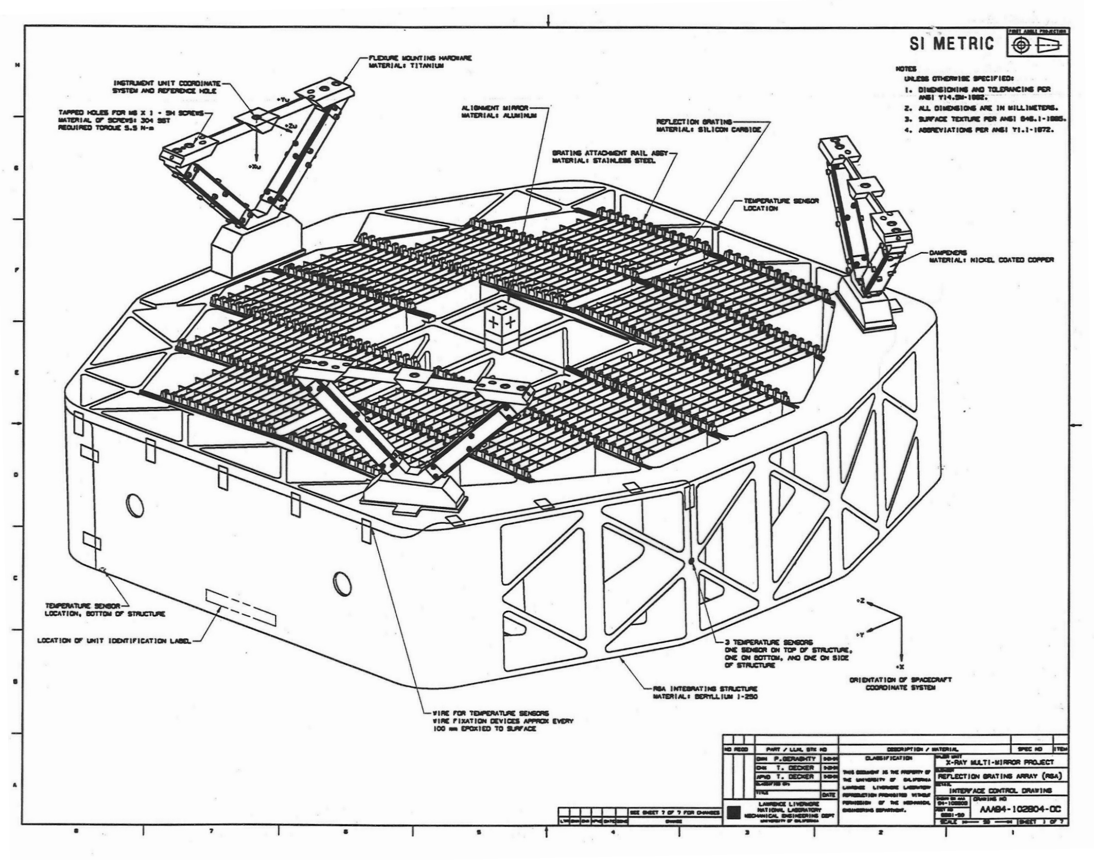
- I asked for a meeting with Charlie Pellerin, the Head of Astrophysics at NASA at the time.
- Charlie was a colorful guy. He could be quite "scary". I was only 30 then, and a beginning assistant professor.
- I described three options to him: (1) He could fund me to act as a consultant to the European groups, who would build the instrument; (2) He could fund me to produce the master grating, which we would then replicate to produce the arrays; or (3) He could fund me to build the whole arrays.
- To my enormous surprise, he liked option (3). Charlie felt that if NASA was going to get involved with XMM, we should do it in a big way.
- The eventual construction project cost $25M.

The Grating Array Design

- I took these ideas out to Lawrence Livermore National Lab (LLNL), which had a fantastic precision mechanical engineering group, and also was interested in getting into X-ray astronomy to build on their weapons-based X-ray physics expertise.

- This is how Chuck Hailey became involved. He helped me rope in some great young engineers: Rick Montesanti and Todd Decker. We came up with a design that involved replicating the gratings onto thin silicon carbide substrates, and then aligning the gratings using precision mounting points on a beryllium integrating structure. The whole thing was supported by three novel kinematic mounts.

- We had to experiment with various vendors to produce the master grating, perfect the epoxy replication technique, and produce the very flat SiC substrates.



Detail of the replicated grating and the precision bosses.

Things that went wrong in the fabrication!

- Getting the master grating right was nontrivial. Because of the variable spacing, we needed to use an interferometrically controlled ruling engine. The pressure and the angle had to be just right to get the desired blaze shape for the grooves. This was mainly trial and error, and it took time.

- Replicating the master faithfully was also a challenge. Our grating vendor, Hyperfine Corp., did fine for a while, but after the first 50 gratings, things started to degrade. We discovered later that the owner of the company did the first 50 himself, then handed the process over to a technician.

- SiC was a relatively new material then, and there wasn't much experience machining it. They broke lots of tools.

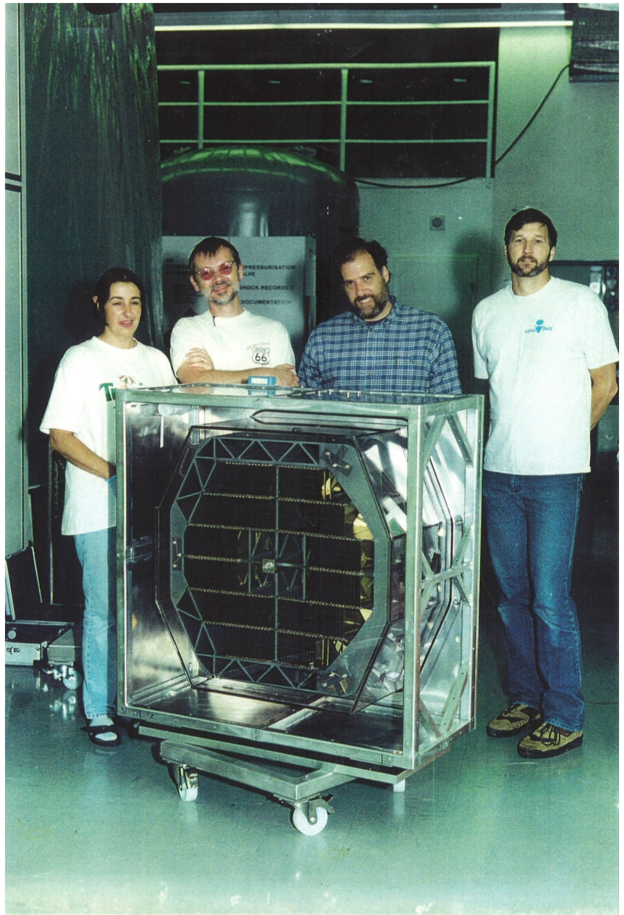
- The beryllium structure was a nightmare. It took a year to fabricate the first blank, which they destroyed just near the end of the process. Then once we got an acceptable blank, we still needed to get it machined. Beryllium is toxic to machine, so not many shops will take it. We started with American Beryllium Company in Sarasota. Then they got bought out by Loral. Then Loral got bought out by Lockheed-Martin. Then LockMart decided to close the company, with our part stuck in the shop. Eventually, we were able to transfer it to Speedring in Cullman, AL, which finished the two structures successfully.

- We built a qualification model, with a real structure, and real gratings, and brought it to GSFC for the first "shake test". We they turned the machine on, there was this god awful noise, and we started yelling "Turn it off, turn it off!" Several of the gratings had turned to dust. This was not good.

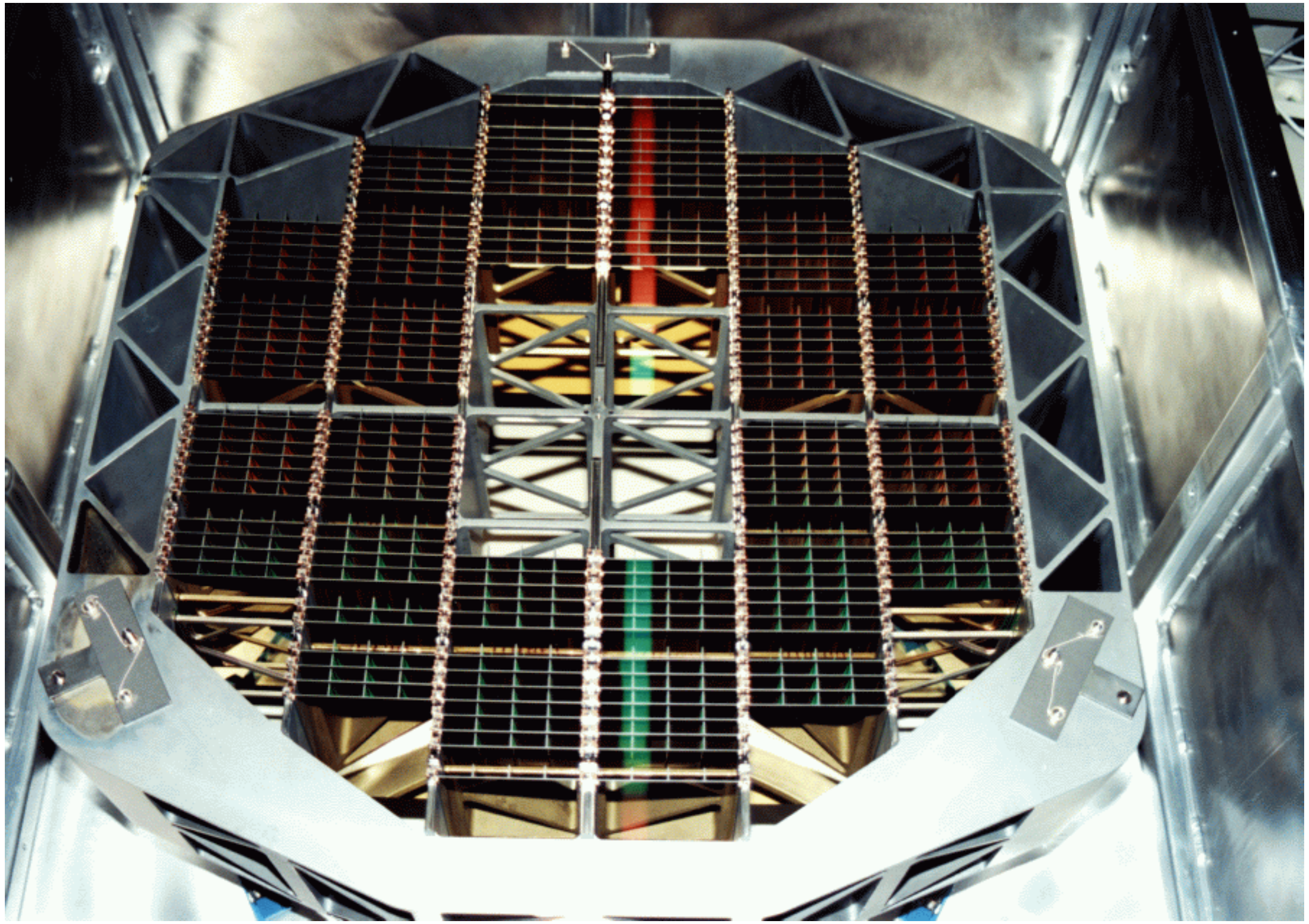
- The problem was with the way we held the gratings against the bosses. We used clips, so that the force would be uniform, preventing the boss from pressing into the gold coating, which would make us lose our precision. But the shake excited the resonance of these clips, so the gratings started banging against the bosses. We fixed it, by using a soft, pliable epoxy to hold the grating in place. But this meant that once we had assembled the array, we could easily take it apart.

The first trip to the Panter facility.

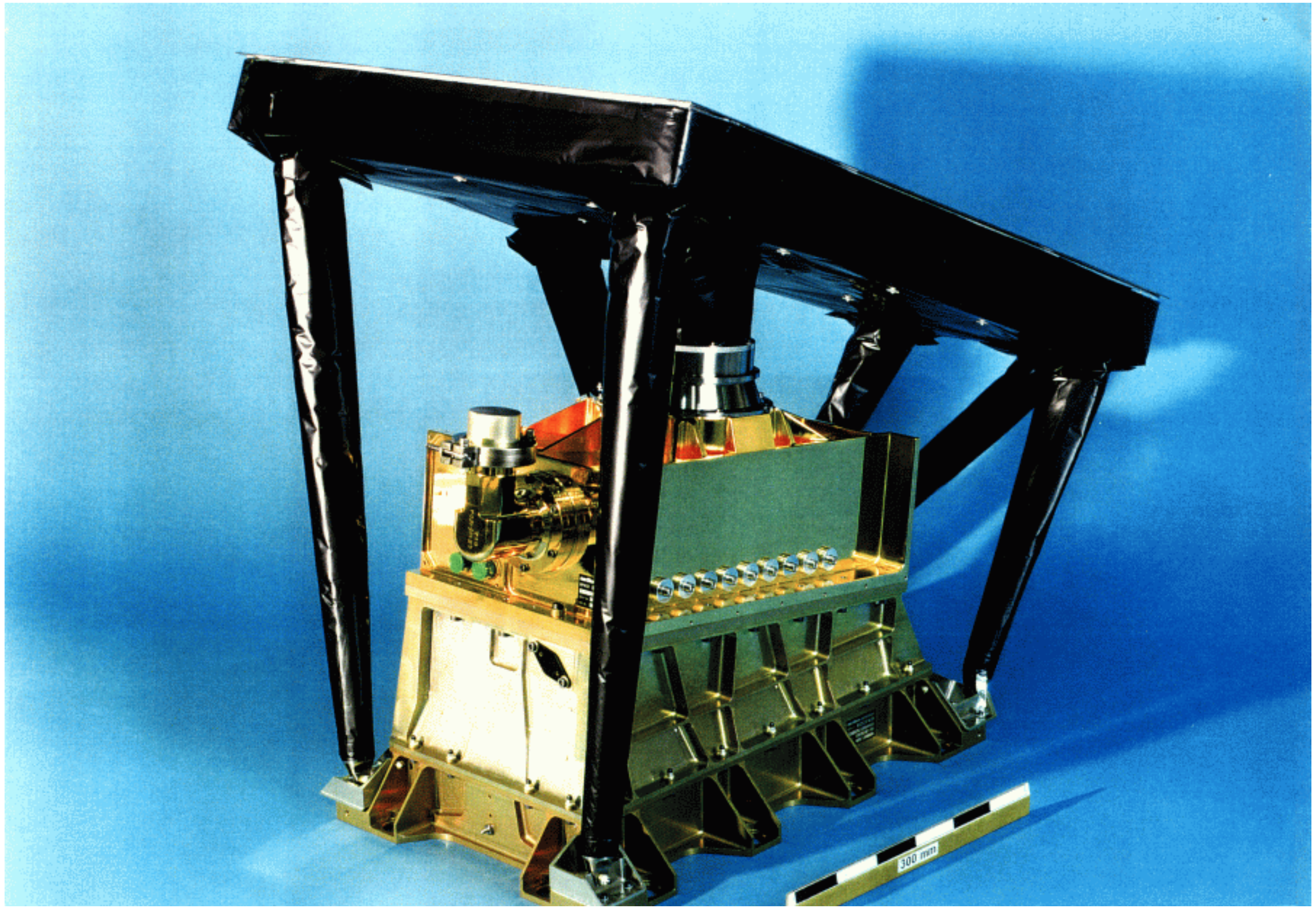
- When we completed the first grating array, we took it to the Panter facility near Munich for the long-beam test with one of the actual mirrors.
- We spent a lot of time on alignment, but once we got everything ready, we started recording line profiles.
- After a short time, it became clear that the array wasn't focusing properly. The Germans and the Dutch didn't seem to make much of a deal of this, but I pulled Frits outside, and said "We're screwed. You know that right!"
- Fortunately, the Germans let us play with the system, moving the array around to see what was happening. We discovered that the array was actually accurately built, just to the wrong figure. It was a Hubble mirror problem, which Andy Rasmussen later figured out was due to the anglular interferometer we had used to align the gratings.
- Once we knew what the problem was, we came up with a very simple fix that involved simply altering the lengths of the flexures. The brought back the expected performance.
- I was embarrassed of the error, but I was proud of how quickly we figured it out and were able to come up with a solution!



The Completed RGS Reflection Grating Array



The Completed RGS Focal Camera



Trip to French Guiana!

- Launch was a blast! A number of us went down to French Guiana for it.
- We were mostly in NY at the time. But to fly directly from NYC to French Guiana, you had to stop in Port-au-Prince Haiti, which was a very unstable place at the time.
- So we decided to fly to Paris, and then back across the Atlantic again. We did this both going out and for the return.
- I actually got quite sick in French Guiana, so the flight back was miserable. As soon as I got home, I told my wife to take me to the hospital, since I thought I had contracted some form of jungle disease.
- The doctors couldn't figure out what it was, but they gave me a bunch of Cipro, and eventually it went away.

Launch!

- My favorite story about the launch:

- Notice that the solid rockets had pictures on them. These were drawn by children, one from each country in ESA. The Swiss picture showed a rocket going over a cow. The ESA PR crew brought the kids down for the launch and interviewed them on TV. They asked the Swiss kid why he had drawn a cow, what did that have to do with XMM? His response was "I like cows."

Launch (cont'd)

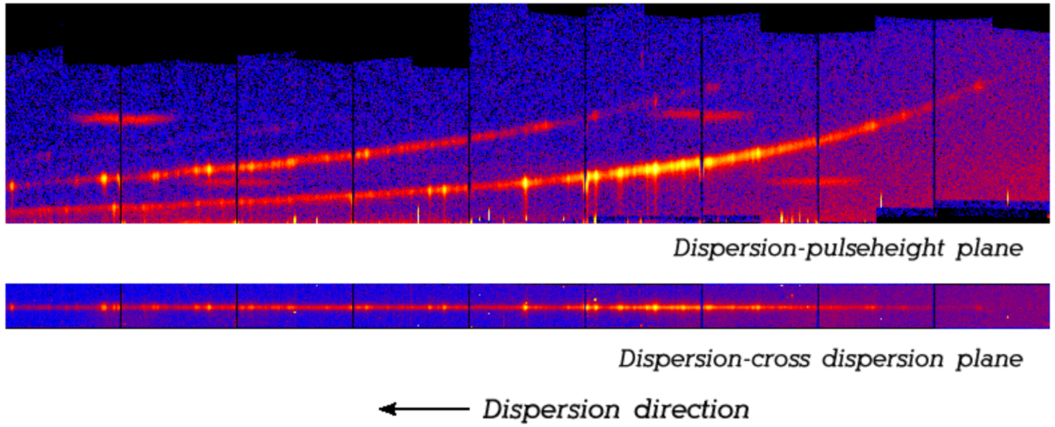
- The launch was scary. The noise was unbelievable.

- The experience was very emotional for me. To see something so delicate, that you had worked so long on go up into space on such an ear-splitting platform was overwhelming. I rank it second only to witnessing the birth of my son.

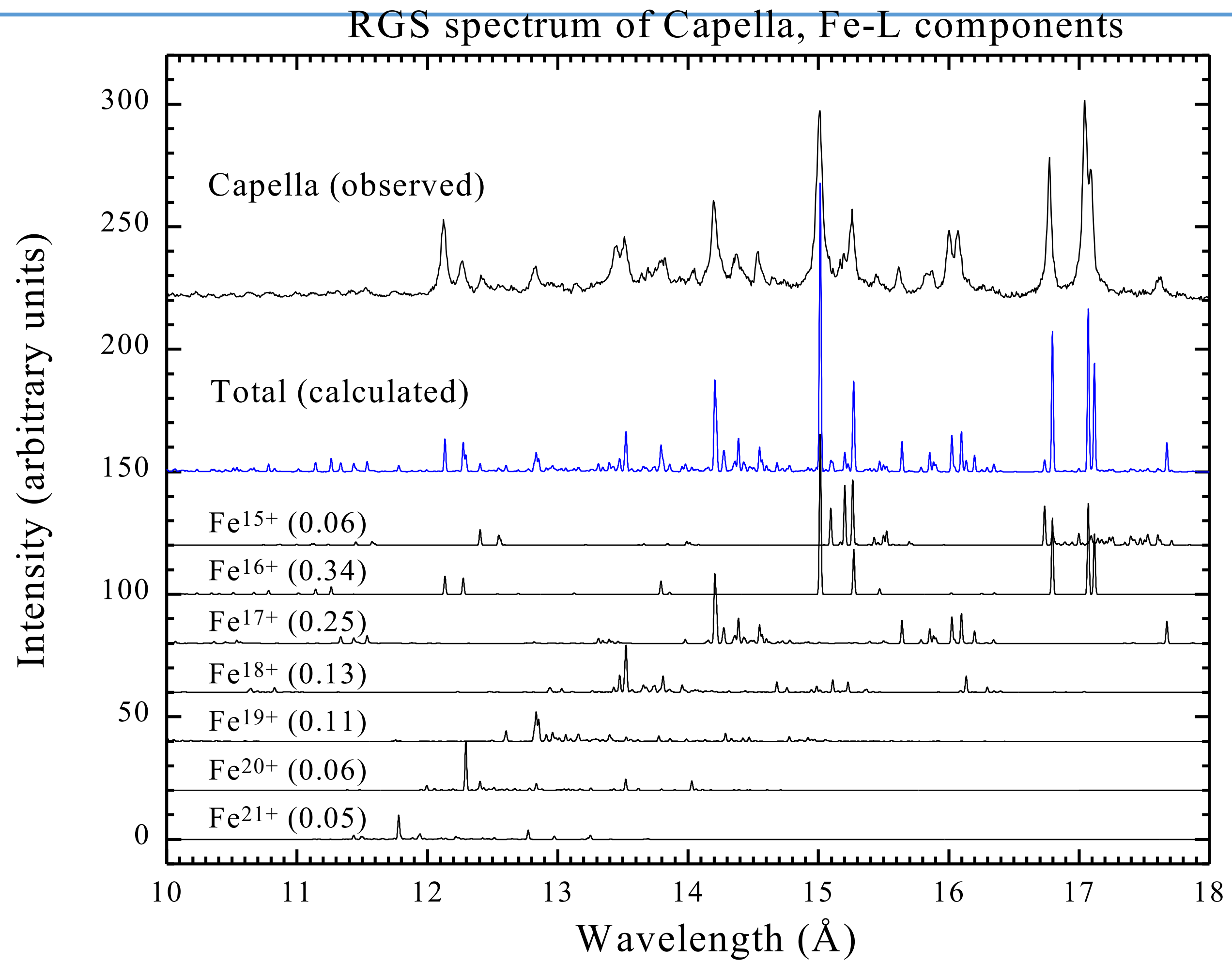
- But we were all nervous about whether the grating arrays had survived. Fortunately, ESA had done something clever: They put a video camera on the satellite. So once it was in orbit, we could see that everything was intact. This was a tremendous relief.

First Light

- The system had to outgas for ~ one month, before we could open the doors to the detectors.
- During that month (which included the Christmas break), I went skiing and broke my leg.
- But I wasn't going to miss first light, so I went to ESOC in Spain on crutches.
- The doors were on springs with a clamp that was disengaged by a pyro. Once the commands were given, the question of how we would know that they had actually opened was raised. Someone figured out that we could look at the reaction wheel data – the small kick from the doors opening created a slight perturbation to the attitude of the whole spacecraft.
- We watched the temperatures go down as the detectors cooled. But we didn't see the first spectrum appear as we expected. Eventually a young Spanish postdoc coaxed a senior scientist to get out of the way, and he sat down at the console, and typed in some commands. The spectrum of HR 1099 popped into view. (The senior scientist wasn't operating the software correctly!)



RGS Observation of Capella - Fe L Complexes



The XMM-Newton RGS team

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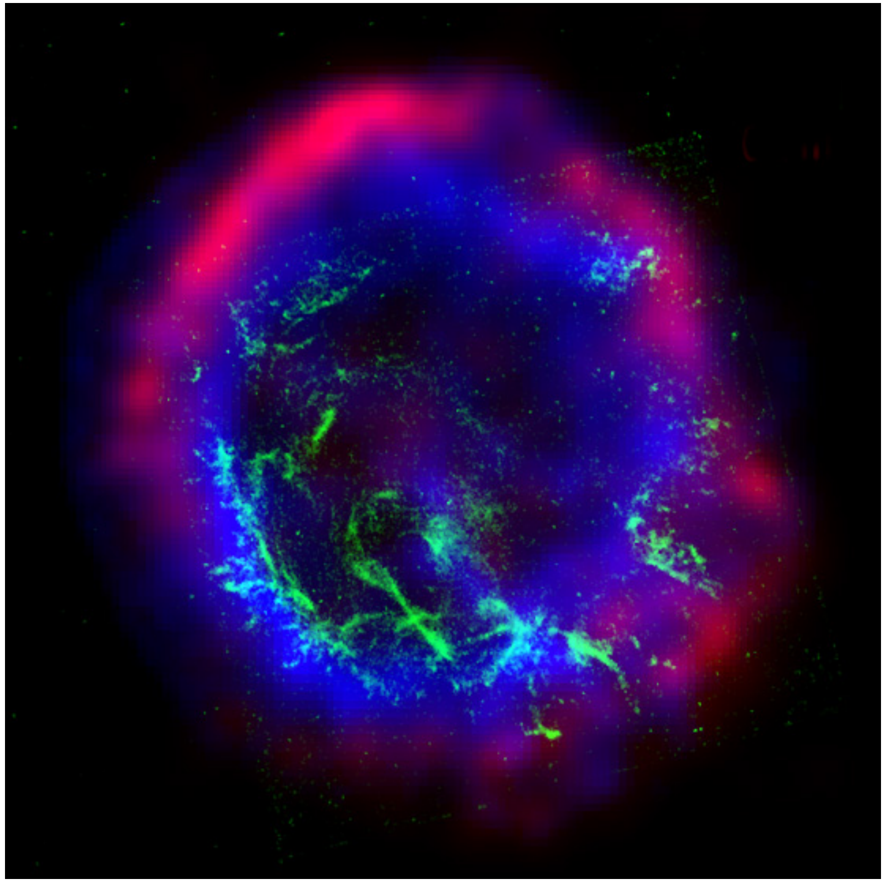

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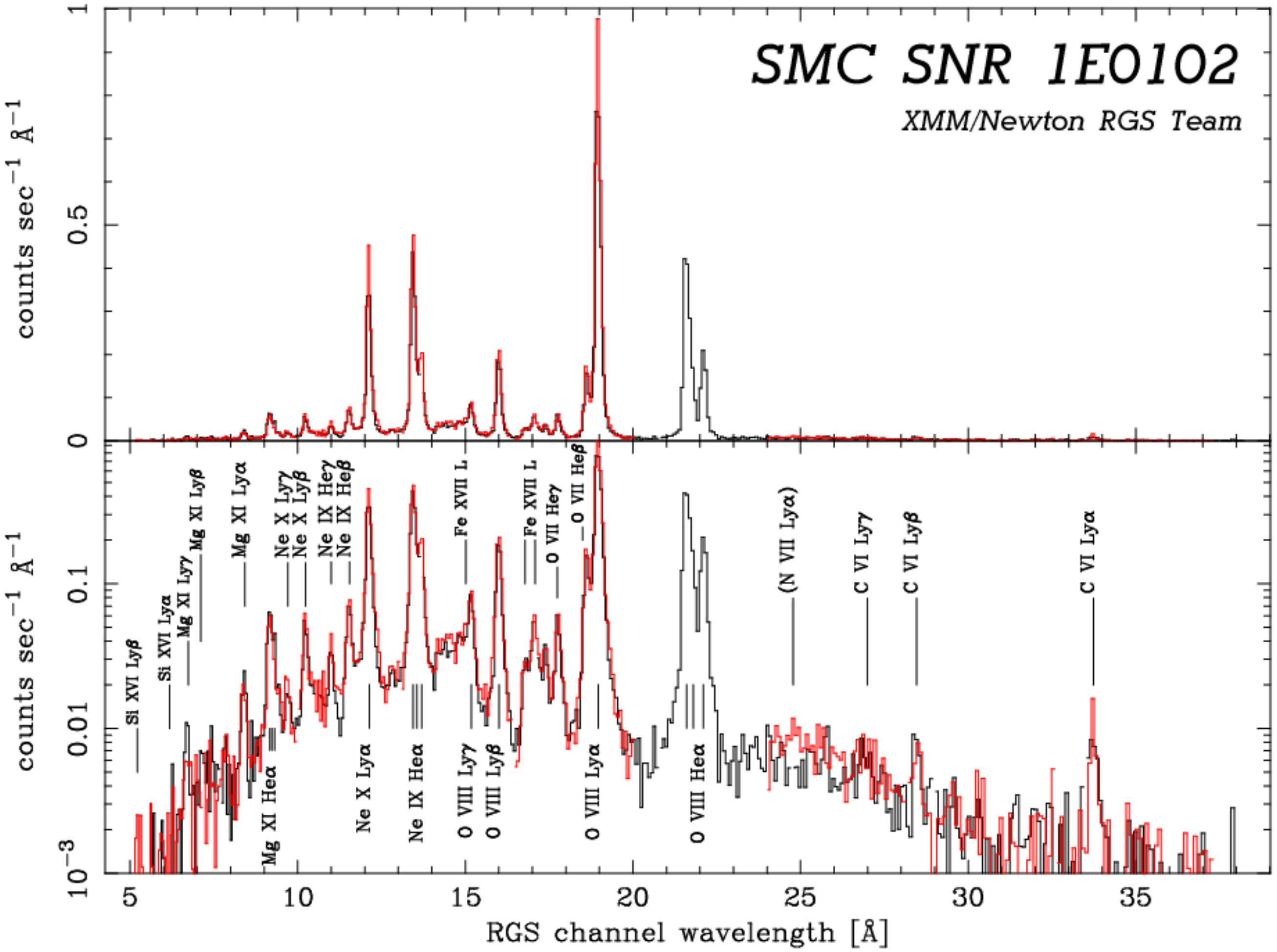

SMC SNR 1E0102
XMM/Newton RGS Team
counts sec^{-1} Å^{-1}
RGS channel wavelength [Å]
Si XVI Lyβ
Si XVI Lyα
Mg XI Lyγ
Mg XI Lyβ
Mg XI Lyα
Mg XI Heα
Ne X Lyγ
Ne X Lyβ
Ne IX Heγ
Ne IX Heβ
Ne X Lyα
Ne IX Heα
Fe XVII L
O VIII Lyγ
O VIII Lyβ
Fe XVII L
O VII Heγ
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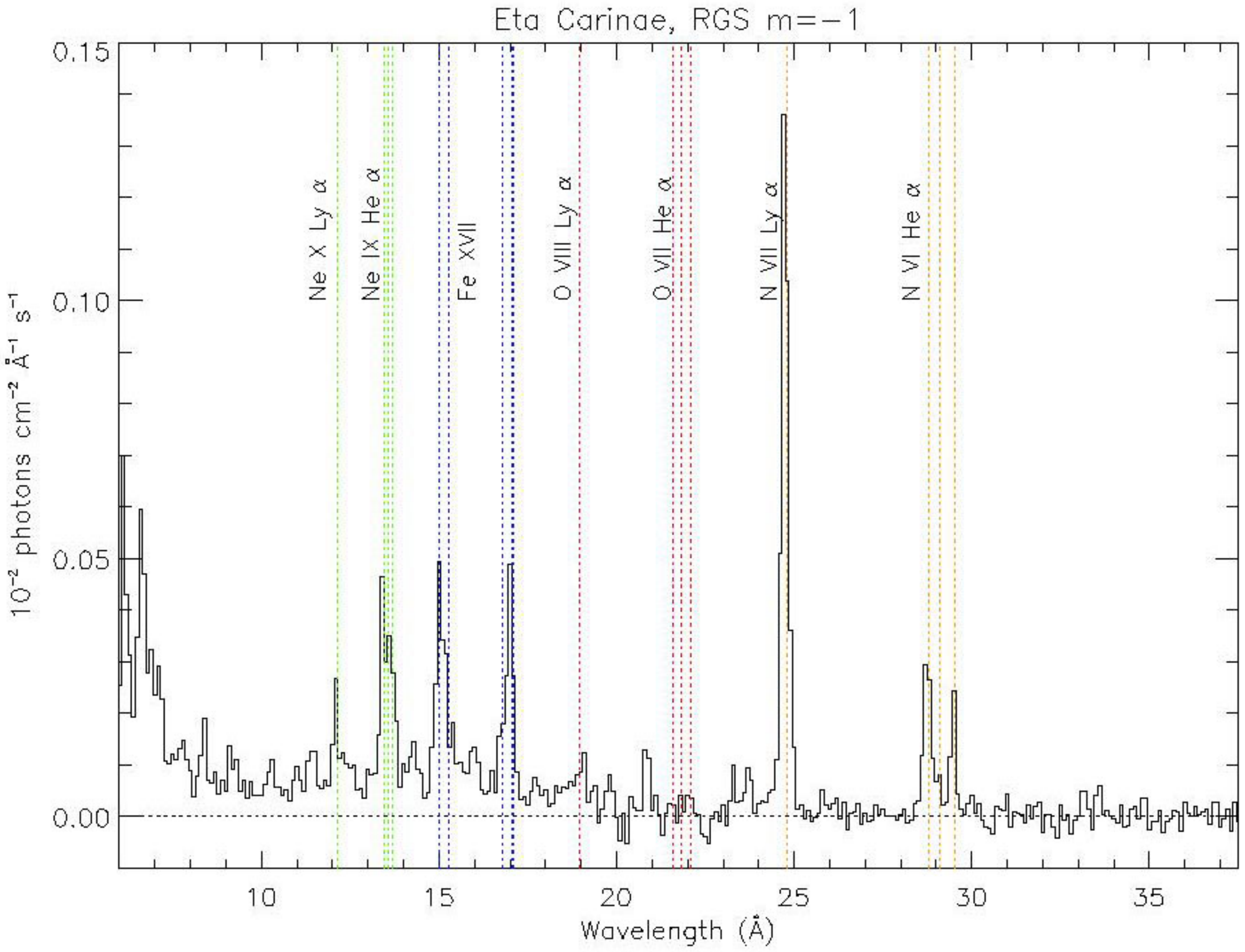
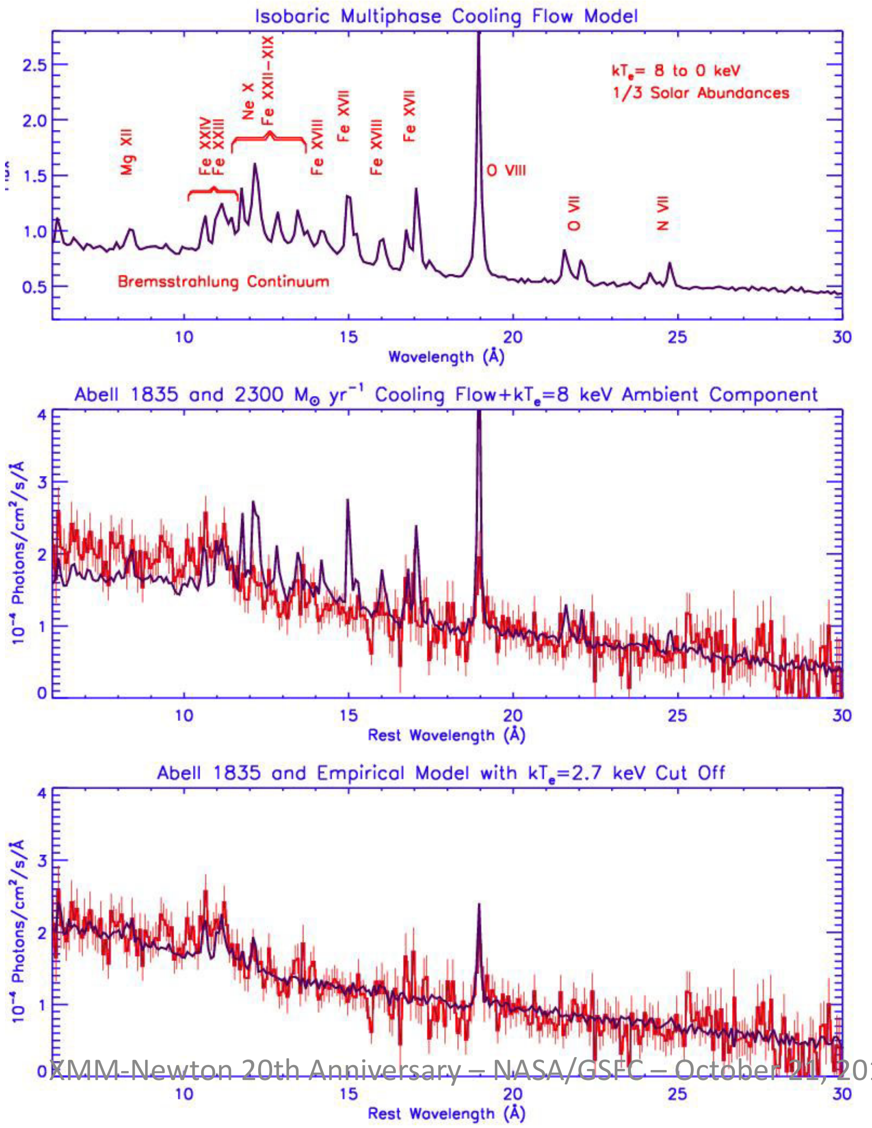
C VI Lyβ
C VI Lyα

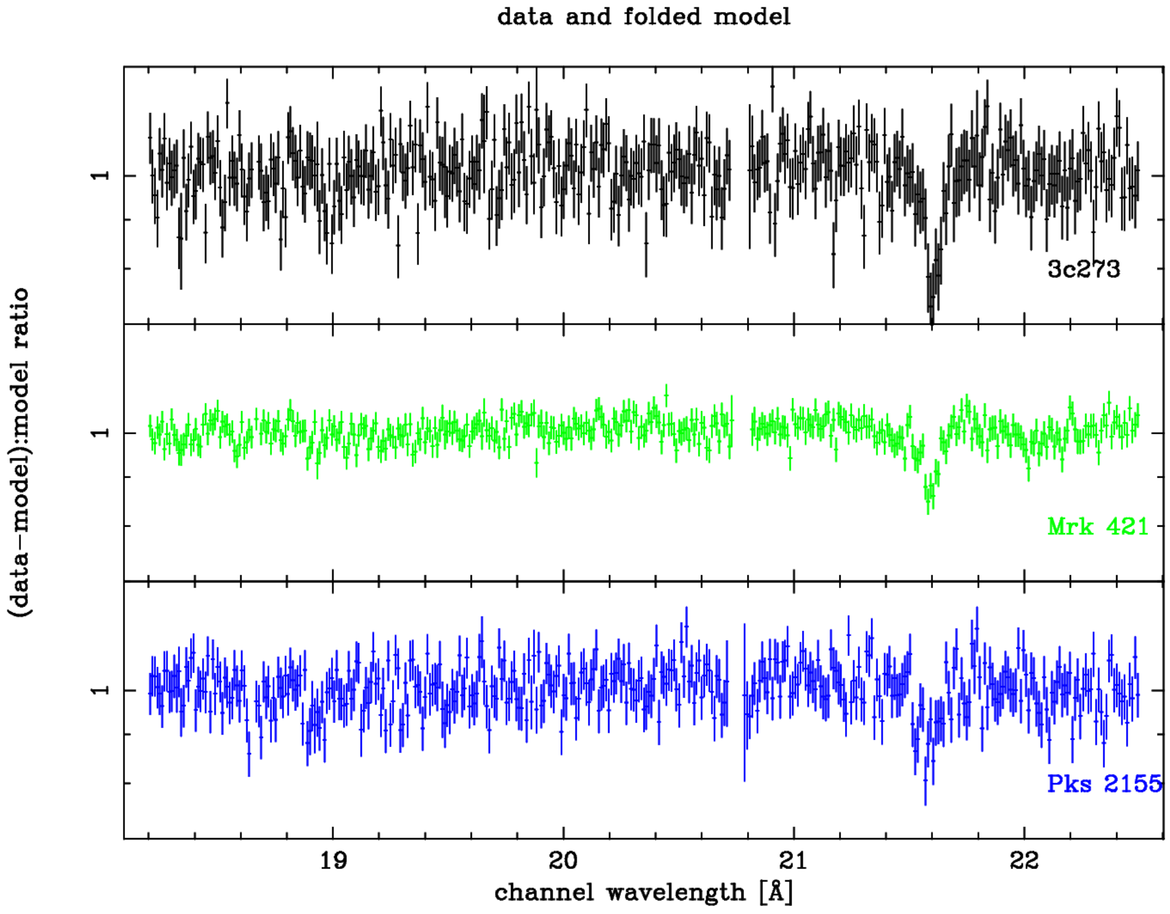
Very High N/O Ratios in η Carina



Lack of Cooling Flows in Clusters of Galaxies



Detection of the Hot Halo of the Milky Way



Summary and Conclusions

- ❊ The development and eventual exploitation of the XMM RGS was the centerpiece of my career in X-ray astronomy.
- ❊ I learned an enormous amount, about how to put an experiment together, how to hang in there, when things go wrong, and how to develop strong and lasting collaborations, both with scientists and engineers.
- ❊ Although I pretty much left the field only a few years after XMM started operating, I have followed the magnificent results that have come from this instrument closely ever since.
- ❊ As X-ray astronomers, we were tremendously lucky to have two superlative observatories operating at the same time, both exploiting the new and emerging field of high resolution X-ray spectroscopy.